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PROJECT APOLLO

A PROPOSED LEM DESCENT TRAJECTORY AND FUEL BUDGET

Prepared by: Donald C. Cheatham
Donald C. Cheatham

Thomas G. Price
Thomas G. Price

Approved: Robert C. Duncan
Robert C. Duncan
Chief
Guidance and Control Division

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

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INTRODUCTION

The identification of desirable features of the LEM powered descent maneuver and the process of understanding the systems required to enable such a maneuver has progressed rapidly since the lunar orbit rendezvous approach was adopted for Apollo. The concept of a three-phase descent as proposed in reference 1 now appears to be accepted although further refinements of the described trade-offs between operationally desirable features and guidance and/or other system optimum performance still continues and probably will continue to some degree until the actual mission date is closely approached. More recently, the improved understanding of the descent has been evidenced by the adoption of a Delta V or fuel budget (reference 2) and a fairly detailed sequence of events as part of the AMPTF effort (reference 3). Additional understanding of the descent maneuver requirements has been gained by the G&C Division through analysis and piloted simulation studies (references 4, 5, and 6). The results of these studies provides the basis for significant refinements to be made to both the descent trajectory and to the fuel budget. It is the purpose of this paper to describe these refinements and to explain their importance to the LEM descent.

PROPOSED NOMINAL DESCENT TRAJECTORY

Phase I

The three phases of a proposed LEM nominal descent trajectory are described by the time histories presented by figure 1 (a, b, and c). Phase I (or Braking Phase as proposed in reference 7) is essentially the same as the corresponding phase from AMPTF Review draft (reference 3).

Phase II

Phase II (or Landing Approach Phase) (figure 1 (b)) is also quite similar to the corresponding phase of reference 3 through most of that descent; the significant difference being in the specified end conditions. The end conditions proposed are 700 feet of altitude, forward velocity of 60 ft/sec and vertical velocity of 15 ft/sec, as compared to 200 feet of altitude and 10 ft/sec forward velocity from reference 3. The significant advantage of the change proposed is that the transition from a pitched-back attitude to an attitude close to the vertical occurs at a higher altitude and thus allows the pilot a much improved view of the landing area earlier than afforded by the trajectory of reference 3. It is believed that an altitude of 200 feet (reference 3) is much too low for the fairly radical attitude transition between Phase II and Phase III. MIT, in their descriptions of this transition, have stated that 200 feet is not firmly recommended but that operational considerations may result in selecting a higher altitude. Landing approach simulation studies conducted by the Guidance and Control Division (reference 5) have allowed qualitative comparison between the two-type trajectories and the proposed trajectory, though not necessarily considered a final answer, was judged to be superior. Several hundred simulated landing approaches were flown by Astronauts and Flight Crew Support pilots during the reference studies.

Phase III

The proposed time history of Phase III (or Final Approach Phase) is shown in figure 1(c) and an altitude range profile is shown in figure 2. The significant feature of this phase is a continuation of the flight path angle established during Phase II flown at an attitude close to vertical. This approach attitude will afford the pilot the best available window view of the landing area and being close to the landing attitude provides a good reference platform to judge the landing situations. The velocities during this phase are gradually decreased until the landing site is reached and just prior to this point, a flare is made to allow the final 50 to 100 feet of altitude to be covered in essentially a vertical descent. Because the nominal touchdown point is close to the extrapolated flight path intersection with the lunar surface, the pilot line-of-sight to the landing site during the latter portion of Phase II remains well within the available window and landing site visibility should be excellent until the final flare is performed.

Relationship of Phase III trajectory to dead-man curves

A fairly important consideration in the design of the final approach to the lunar surface is the relationship to so-called dead-man's curves. These curves define the combination of altitude, vertical velocity, and staging time for which an abort is not feasible because the ascent engine cannot arrest the vertical descent prior to the LEM hitting the surface. Dead-man's curves for various staging times are shown on figure 3. These curves do not include any operational consideration for the amount by which the surface should be cleared to avoid descent engine debris. The figure also includes a plot of the altitude-vertical velocity relationship of both the proposed trajectory and that of the AMPTF Draft. Assuming that a total staging time (recognizing the failure, initiating staging action and accomplishing staging) of 4 seconds is reasonable, it appears that the AMPTF trajectory is uncomfortably close to the dead-man's curve almost continuously. The proposed trajectory does stay within the proper boundary for most of the final descent but it is apparent that any approach trajectory must violate the curve (although the time so exposed does not have to be long) just prior to touchdown.

Impact upon guidance mechanization

The proposed nominal descent trajectory is believed to impose no new hardships upon the guidance or control mechanization. Phase I represents no change. The change in end conditions of Phase II should be easily accommodated by the guidance system. Phase III, although longer in duration than the corresponding phase of reference 3, presents a comparatively simple task of programing and should not burden the system.

PROPOSED LEM DESCENT FUEL BUDGET

Proposed Nominal Trajectory Requirements

The characteristic velocity requirements of the three-phase trajectory proposed above and the AMPTF Draft Review are as follows:

		Proposed	AMPTF
Phase I		5024	5005
Phase II		950	1050
Phase III		455	336
	Total	6429	6391

The small difference in the Phase I numbers are attributed to slight difference in end conditions and computational approach. Phase II of the AMPTF Draft required 100 ft/sec more than the approach proposed but this is primarily due to the different end conditions. This difference is almost reversed for Phase III where the proposed trajectory takes about 119 ft/sec more than the AMPTF. The important result is that for practical purposes the total fuel requirement is essentially the same and minor changes in assumption could account for any differences indicated.

Contingency fuel requirements

The nominal trajectory fuel requirements as described above, are close to a theoretical minimum for the operational constraints inherent in the three-phase descent approach. From a practical standpoint, it is necessary then to allow for both anticipated and unanticipated contingencies and also for identifiable features of the approach trajectory not described by the nominal profiles. Anticipated contingencies and the fuel allotted are as follows:

Off nominal guidance performance (Phase I and II)	50 ft/sec
Off nominal descent propulsion (All phases)	75 ft/sec
Alternate site selection (Phase II)	120 ft/sec

Landing point inspection (Phase III)		100 ft/sec
Fuel depletion margin (Phase III)		75 ft/sec
	Total	420 ft/sec

The off-nominal guidance performance allowance provides for errors in attaining desired initial condition at the start of powered descent and errors attributable to inertial system drift during the powered descent. The magnitude does not reflect a rigorous solution of the off-nominal performance but rather a conservative guess based upon expected system performance. The off-nominal descent propulsion allottment represents a 1 percent error allowance. The allottment for alternate landing site selection provides for about a 5000 feet change in landing site position to be made at an altitude of 5000 feet. Reference 4 shows this takes approximately 100 ft/sec, however, this is considered a conservative figure as a latter analysis presented in figure 4 shows that considerably more range may be obtained using the LEM primary guidance if it is not constrained by attitude or thrust level limitations. The remaining 20 ft/sec allows a subsequent refinement to be made as the landing site is approached. The landing point inspection allottment provides for about 20 seconds of hovering time to allow a detailed look at the site prior to final descent. This allowance could also provide for a slight dog leg in approaching the landing site in the event that a side perspective of the site was desired in addition to the perspective afforded by a straight in approach. The fuel depletion margin (about 15 seconds) is justified because the crew would be unwilling for the fuel remaining indicator to closely approach an absolute fuel depletion mark. This margin would probably be much greater if there is not an accurate fuel quantity gauge available to the pilot.

For unanticipated contingencies, it is believed that 240 ft/sec (about 45 seconds of hover) is a reasonably conservative allottment. At one time in the LEM tank sizing requirements, there was an implication that two minutes of hover time was provided. This however, was to provide for many of the contingencies listed above and also was quite widely minconstrued to mean a hover capability after reaching the landing site. In fact, however, it was associated with a hover at an altitude of 1000 feet and a conservative letdown from that altitude would easily have expended $1\frac{1}{4}$ minutes of the 2 minutes of hover fuel. Thus, the 45 seconds of hover contingency allotted in the present proposal is considered conservative.

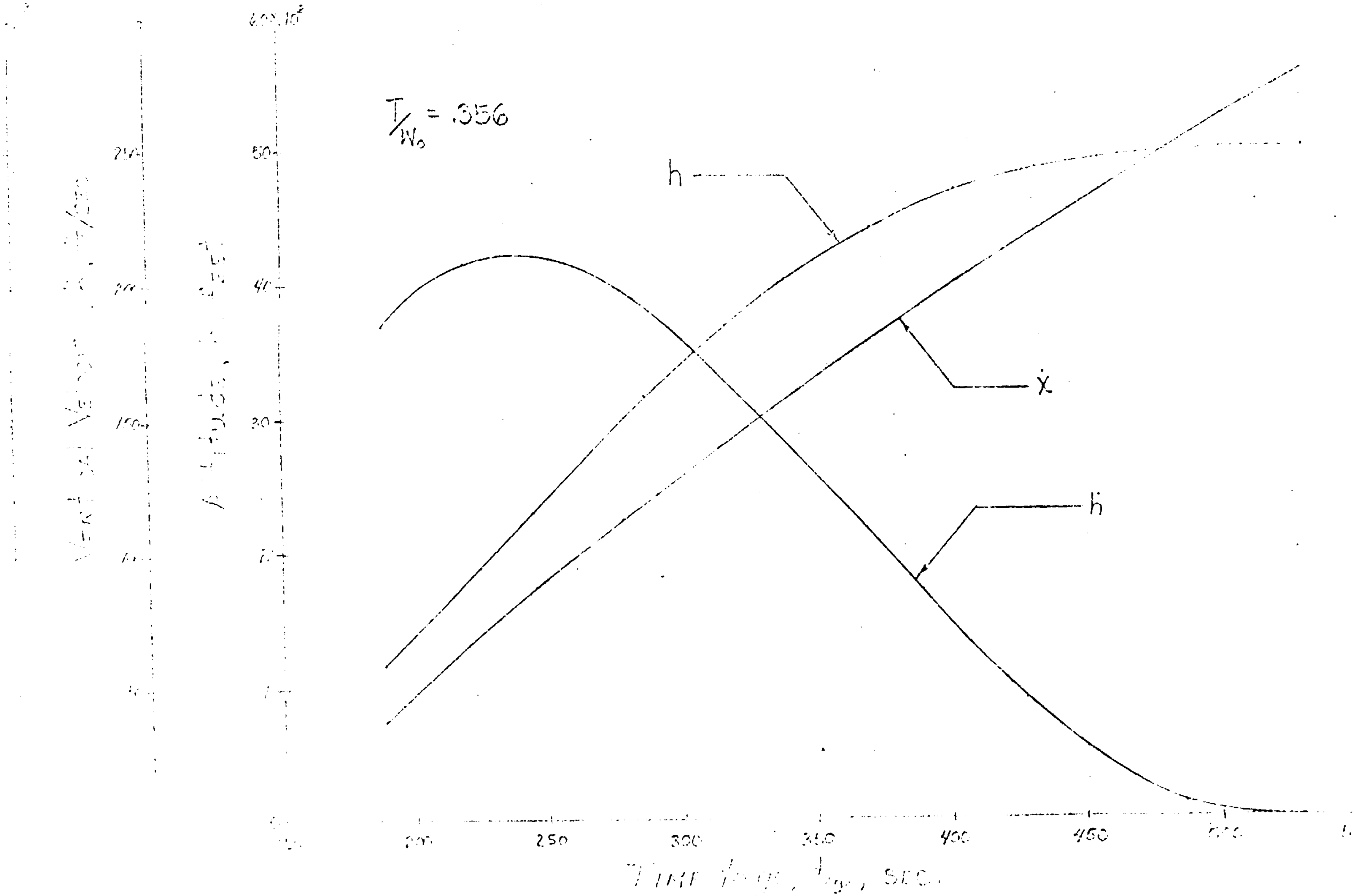
In actual practice, it is expected that considerable additional flexibility in choosing an alternate landing site exists during Phase III without large fuel costs. This flexibility should be present because the pilot can choose to maneuver the LEM with larger attitude changes than that assumed in the nominal trajectory and can safely choose to alter the velocity schedule with which he translates over the surface in approaching a landing site. An example case from the work of reference 1 shows that a range extension of about 3000 feet can be accomplished at a cost of only 42 ft/sec if the pilot is free to maneuver with attitude deviations from the vertical of ±30 degrees. Reference 1 assumes a Phase III descent from 1000 feet of altitude but the range extension capability is qualitatively applicable to the present proposed trajectory.

Influence upon LEM fuel budget

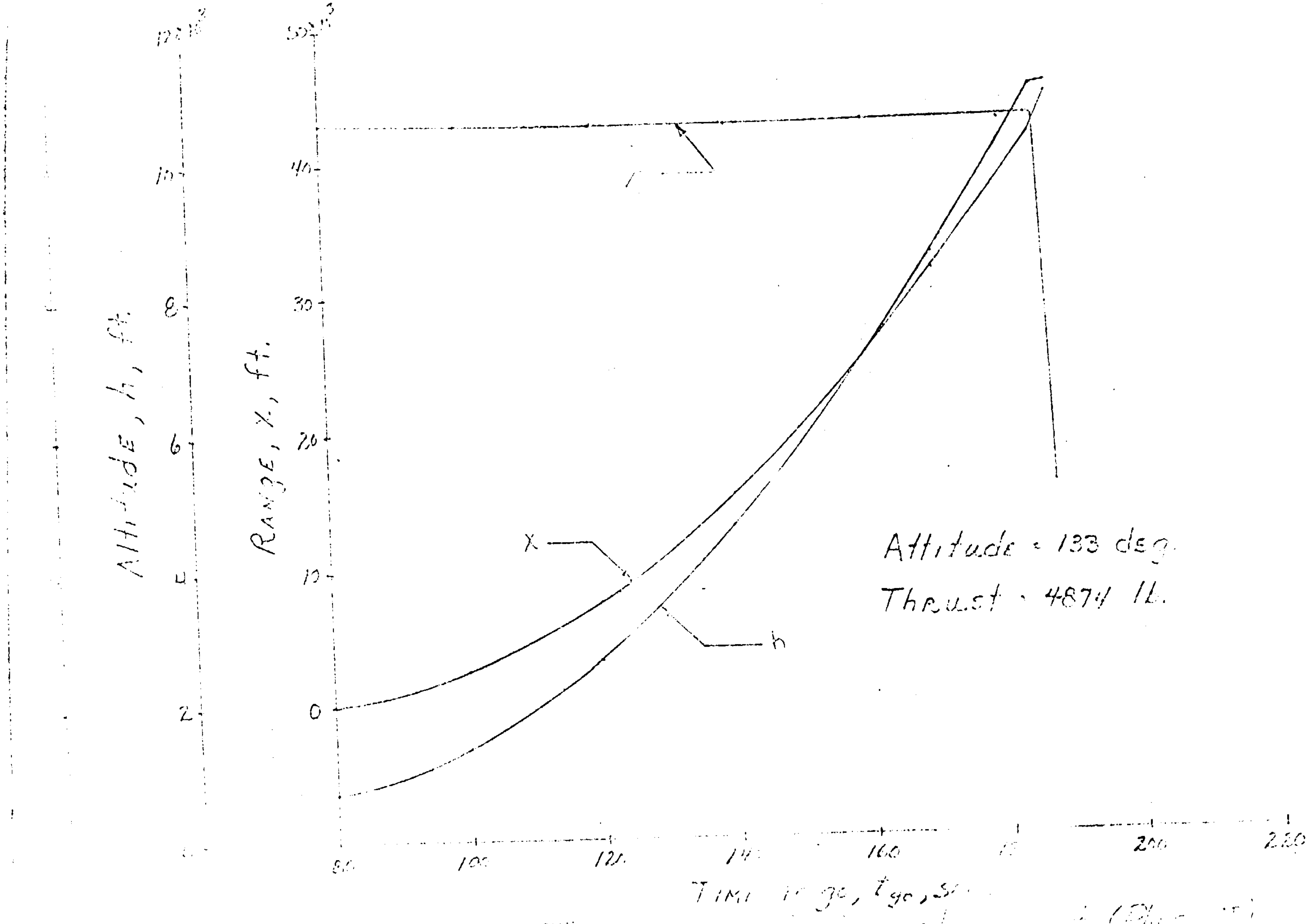
The present LEM descent fuel budget totals 7385. The total of the nominal trajectory requirements and the contingencies listed above is 7207 ft/sec. In addition, allottment of 5 ft/sec for separation from the CSM, 98 ft/sec for the Hohmann transfer maneuver and 15 ft/sec for the rotation of the moon is necessary. The total budget allottment is described in Table 1. There remains a difference of 178 ft/sec of fuel for which a requirement has not been identified. While there will certainly be a reluctance to reduce the fuel budget of the LEM, it is believed that the budget should reflect a logically derived set of requirements. With the present unfavorable LEM weight situation, it appears that a rather significant weight reduction can probably be made.

CONCLUDING REMARKS

The foregoing proposals for a LEM nominal descent trajectory and a LEM descent engine fuel budget are based upon experience gained by independent study by the Guidance and Control Division coupled with knowledge of the work of MIT and GAEC (including AMPTF). It is recommended that the changes proposed be carefully considered by other MSC organizational elements and endorsed as appropriate.



$T/W_0 = .356$
h
$\dot{x}$
$\dot{h}$
250
300
350
400
450
50
40
30
200
150



Altitude, h, ft
Range, x, ft.
Time to go, t_{go}, sec
Attitude = 133 deg.
Thrust = 4874 lb.
x
h

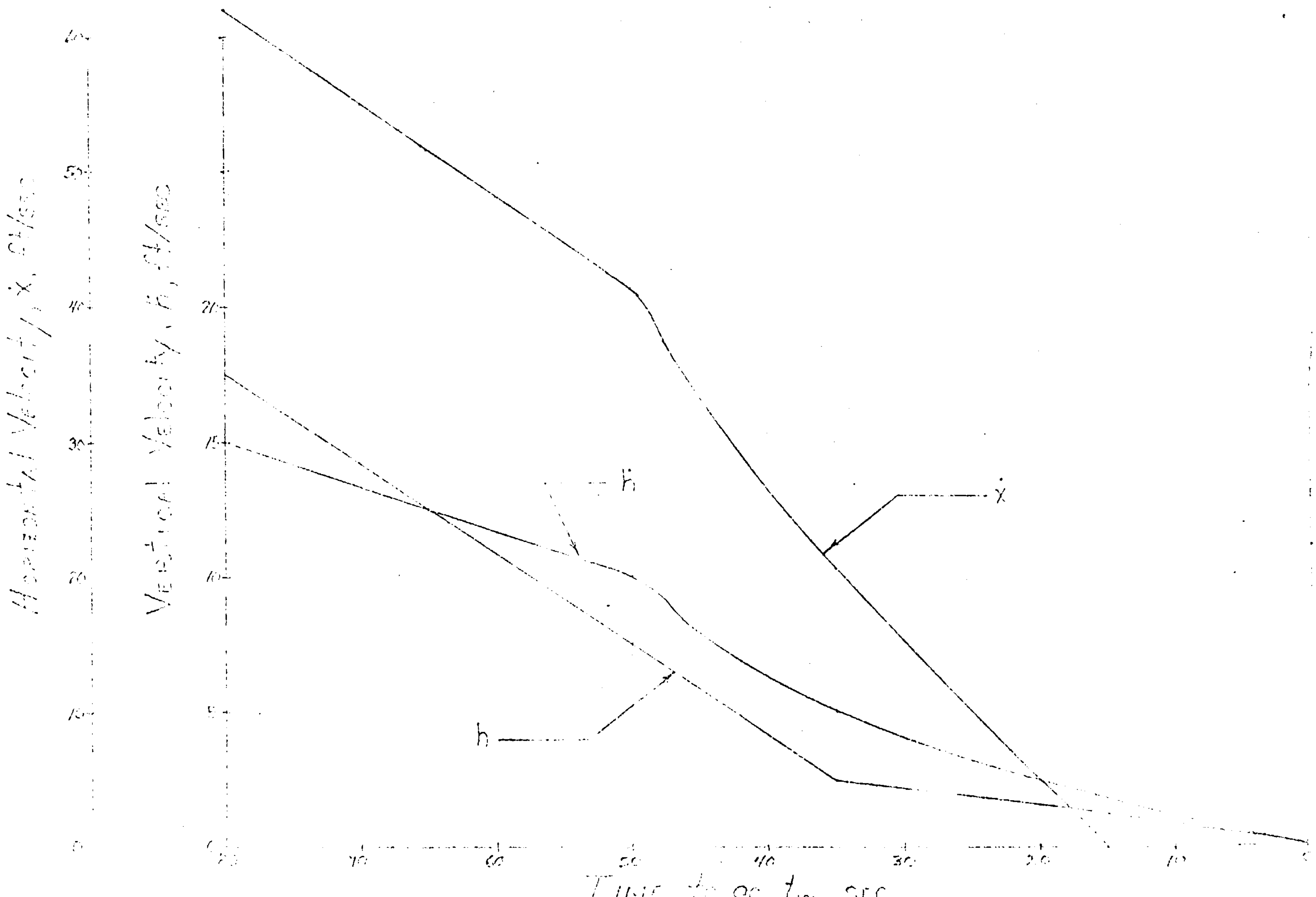
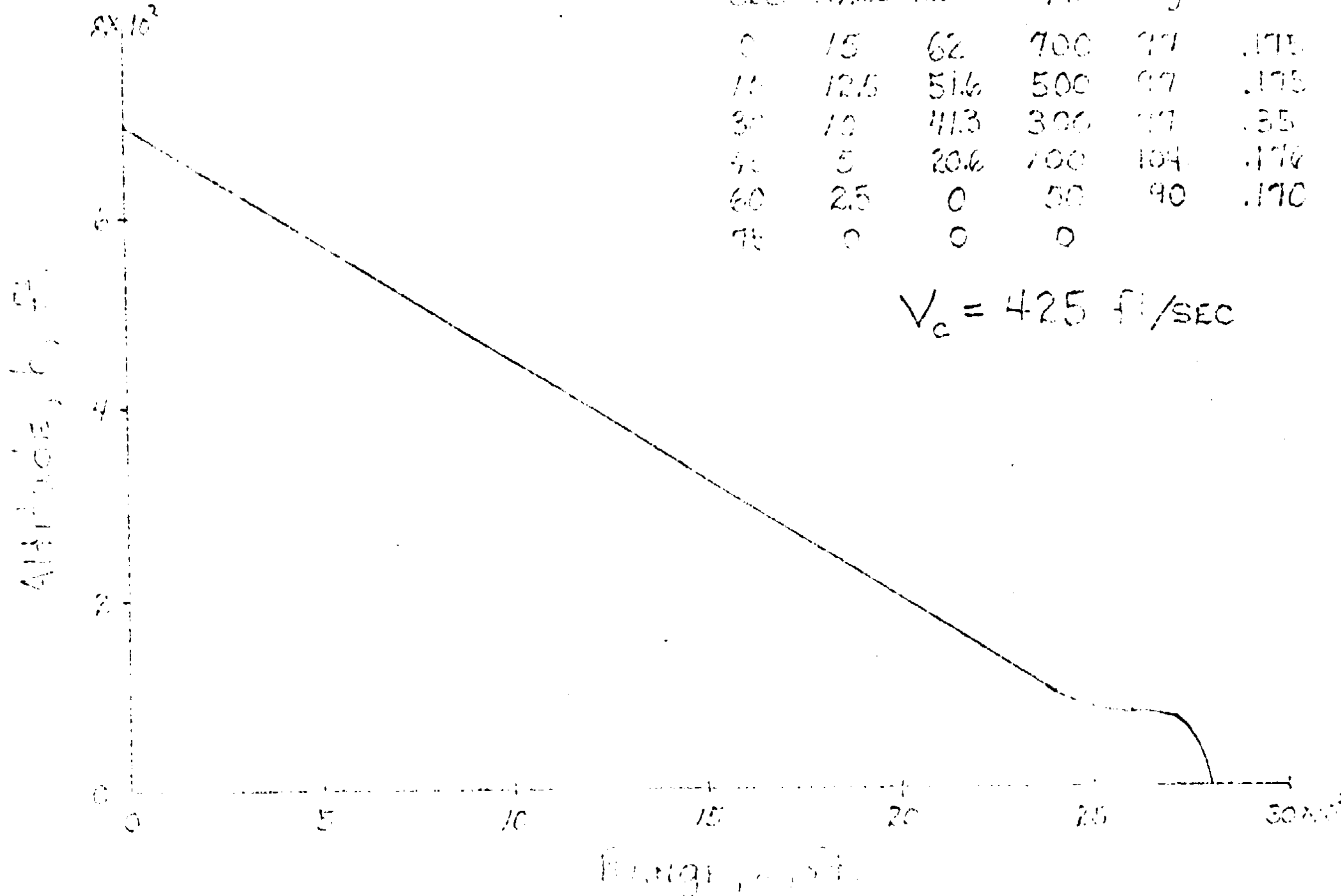


Figure 10. Time History of Powered Descent (...)



t, sec	$\dot{h}$, ft/sec	$\dot{x}$, ft/sec	h, ft.	ε, deg	T/W
0	15	62	700	97	.175
15	12.5	51.6	500	97	.175
30	10	41.3	300	97	.35
45	5	20.6	100	104	.176
60	2.5	0	50	90	.170
75	0	0	0		

$V_c = 425$ ft/sec

Figure 2 - Range vs Altitude for [illegible]

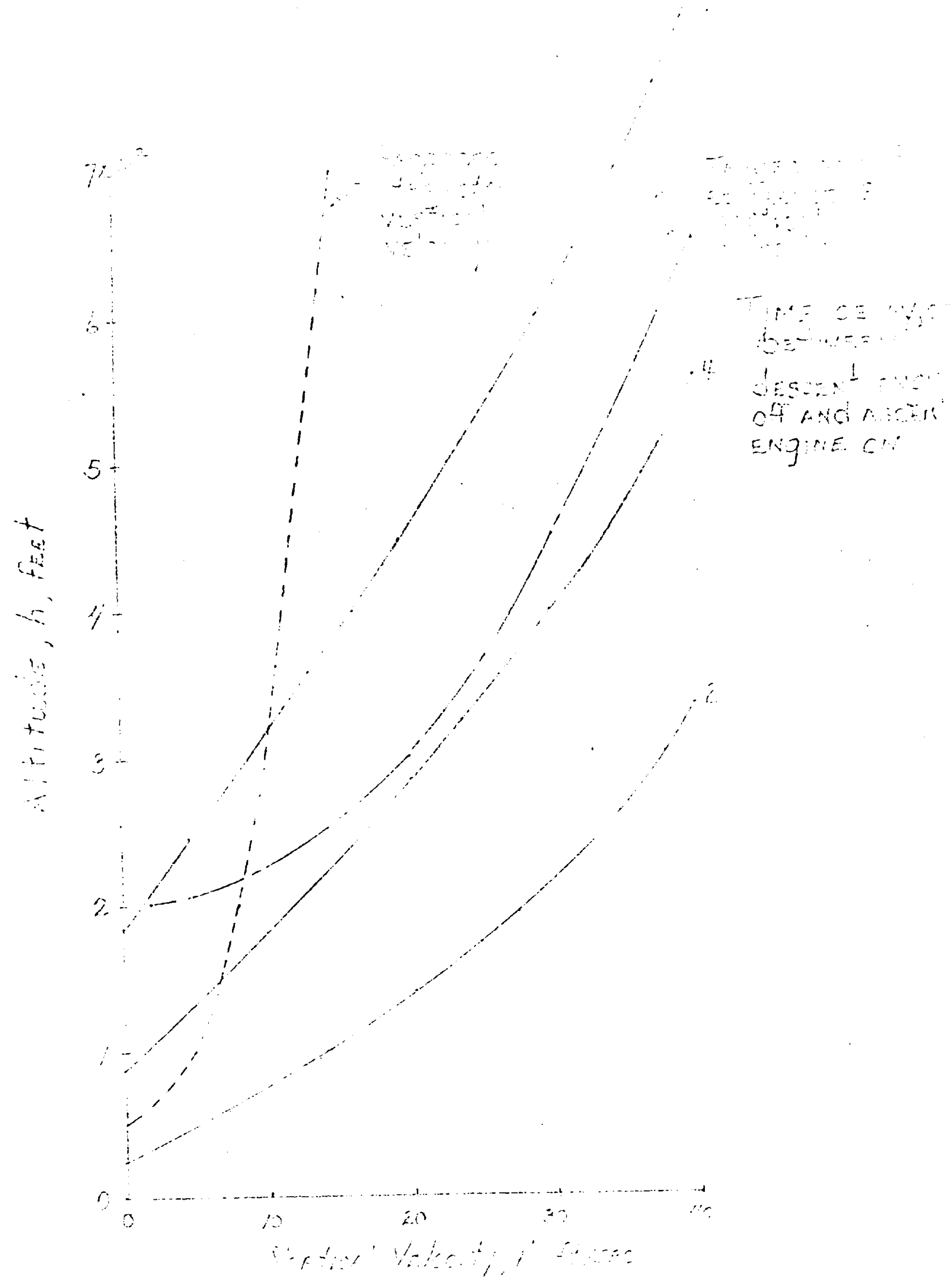


Figure 3 - Dead Man's Curves for LEM Abort Close to Lunar Surface. The [illegible]
[illegible]

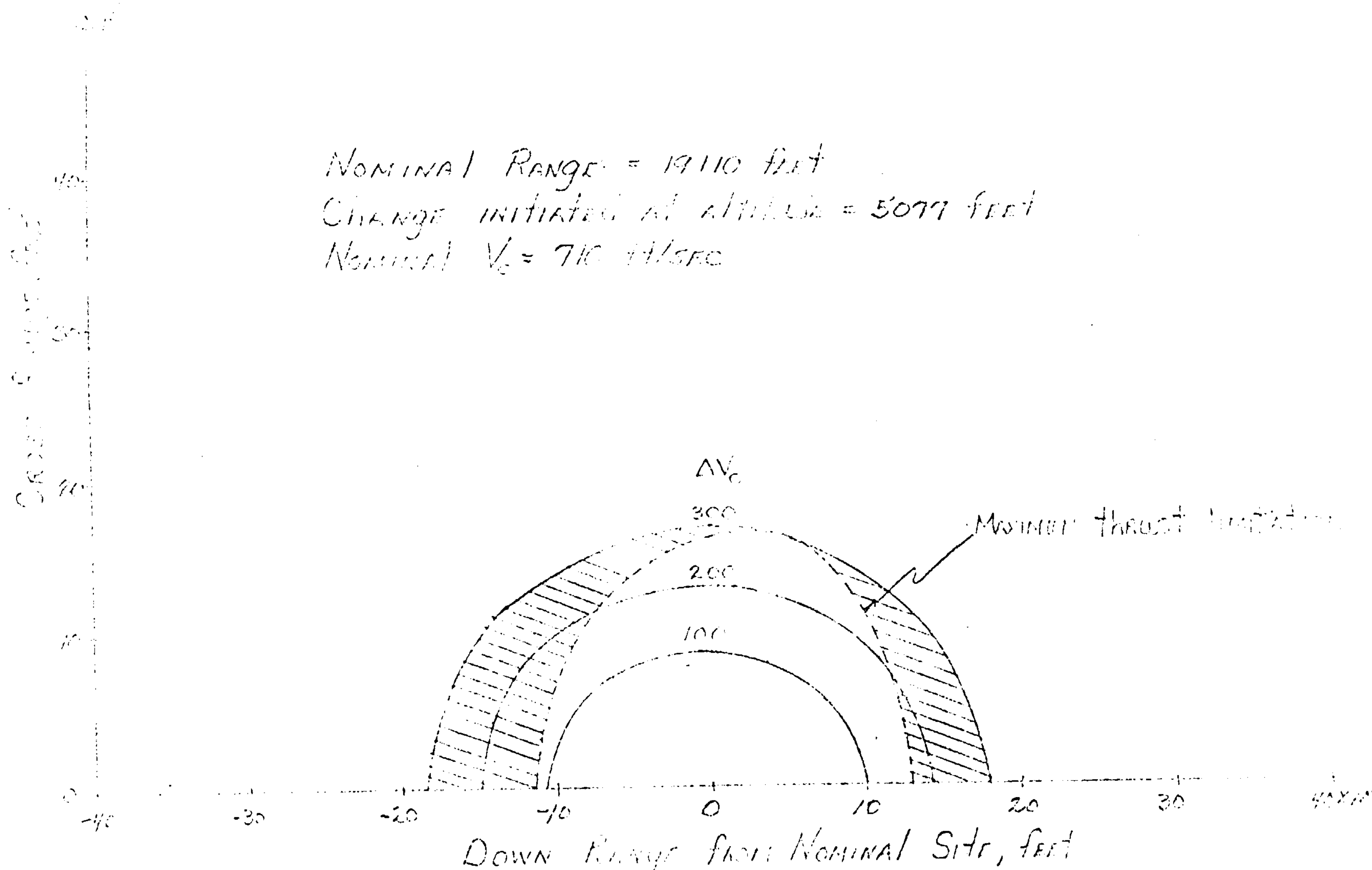


Figure 4 - Footprint for correction made at altitude = 5077 feet

TABLE I

Proposed LEM Descent Fuel Budget

Separation from CSM	5
Hohmann transfer	98
Moon rotation	15
Phase I	5024
Phase II	950
Phase III	455
Off-nominal guidance performance (Phase I and II)	50
Off-nominal descent propulsion (all phases)	75
Alternate site selection (Phase II)	120
Landing point inspection (Phase III)	100
Fuel Depletion Margin (Phase III)	75
Unanticipated Contingencies	240
Total	7207

REFERENCES

1. NASA TN D-2426, "Study of Powered-Descent Trajectories for Manned Lunar Landings, by Floyd V. Bennett and Thomas G. Price, dated August 1964.

2. MSC Internal Note No. 64-FM-47, "Apollo Spacecraft Required Velocity Budget", by James J. Taylor, Harold D. Peck, and Morris V. Jenkins, dated October 16, 1964 (CONFIDENTIAL).

3. Apollo Mission Planning Task Force, LEM Hover-to-Touchdown Phase, Grumman Aircraft Engineering Corporation, dated October 1, 1964.

4. Apollo Working Paper No. 1106, "An Analytical Study of the Landing Footpring Available during LEM Lunar Landing Approaches", by Thomas E. Moore, and Donald C. Cheatham, dated January 16, 1964.

5. Memo, EG23-64-83 to PA/Manager, Apollo Spacecraft Program Office, "Revised LEM Touchdown Landing Criteria", dated August 20, 1964

6. MSC Internal Note EG-64-26, "Effect of Terrain Variations of Primary LEM Guidance Equations During Phase II of Powered Descent", by Floyd V. Bennett and Jack Funk, dated November 9, 1964.

7. MSC Internal Note 64-EG-27, "A Proposed Terminology for the LEM Powered Descent and Landing Maneuver", by Donald C. Cheatham, dated November 23, 1964.